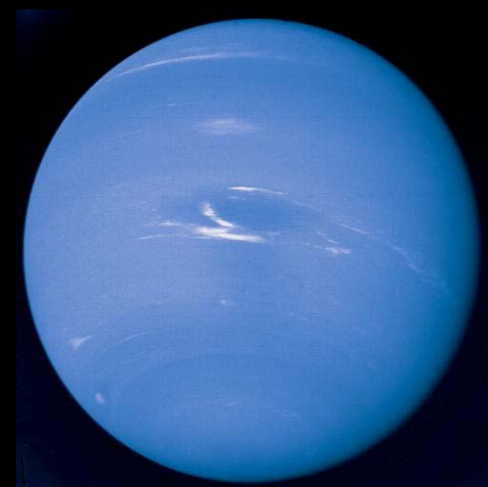
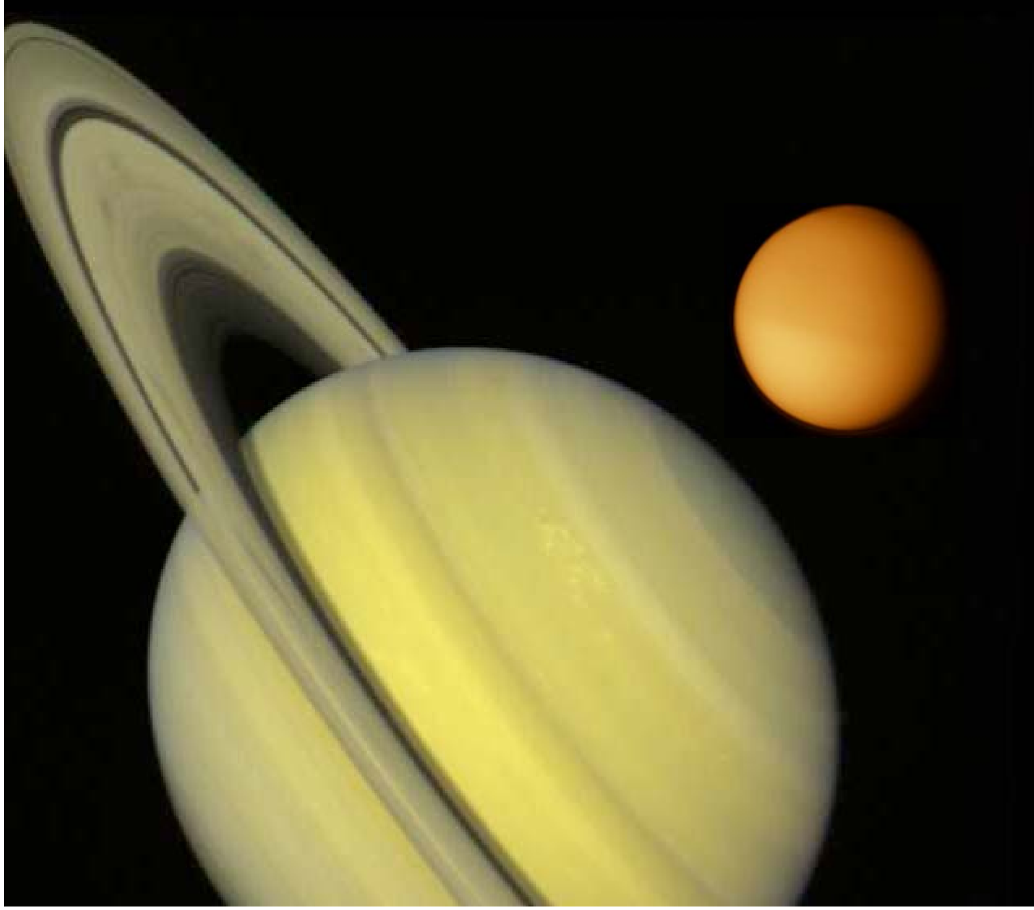
In-Space Propulsion Program
Advanced Sensor Project

Current Developments in Future Planetary Probe Sensors: Update 2004
August 23-26 2004
Moffett Field, CA USA





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Outline

- Overview & Background
- Sensor System Development
- Sensor Testing
- Future Developments
- Summary

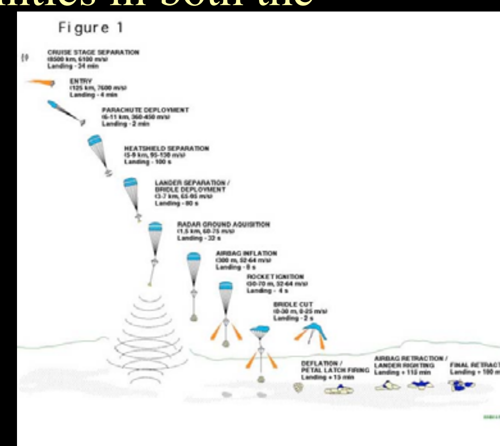
Overview

- Entry Probes require Thermal Protection Systems which are a *single point of failure*
- Risk *reduction* requires risk *quantification*
- Risk quantification requires *entry physics sensors*
  - TPS/Aeroshell Design Performance must be quantified
    - Flight Data + Math models + Ground test data
  - Traceability is enabled by quantification of performance from Ground through Flight
    - Requires an unbroken chain of comparisons between:
      - Aerothermal CFD, materials response models, ground test, and flight
    - Requires a sensor system that can be used from Ground and Flight to enable the unbroken chain.
- Columbia - recovered sensors allowed us to reconstruct events
- DS2 - No sensors and no knowledge to reconstruct or improve

Background

- Significant uncertainties (and risk) exist with heatshield design
- No ground based simulator can replicate *total* flight environments with high fidelity
  - Stagnation pressure *vs*
  - Heat flux *vs*
  - Convection heat load (turbulent,   laminar) *vs*
  - Radiative heat load (emissivity, catalycity) *vs*
  - Enthalpy

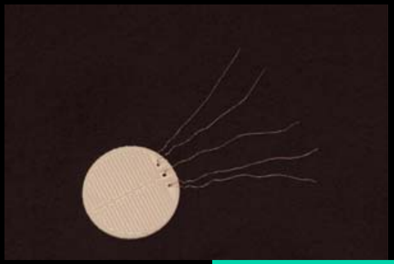
- TPS designs include significant “margin” to account for uncertainties in both the aerothermal environment and material performance



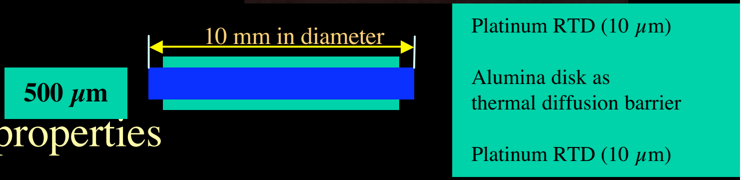
- Penalty in predictive uncertainties is paid with mass and/or risk
  - TPS mass trades directly with mission/science payload
- Reductions in existing uncertainties requires traceability
  - (flight data)
- The largest uncertainties are with the aft-body flow around blunt-body vehicles
  - Design margins of 300%+ are used on aft-body heating rate predictions for past and current Mars entry aeroshells (MPF, Mars ‘03)
  - Contrast this with 25 - 50% margins on the heat shield
  - After-body TPS to heatshield TPS mass fraction is ~40% for MER and ~30% for Pathfinder.

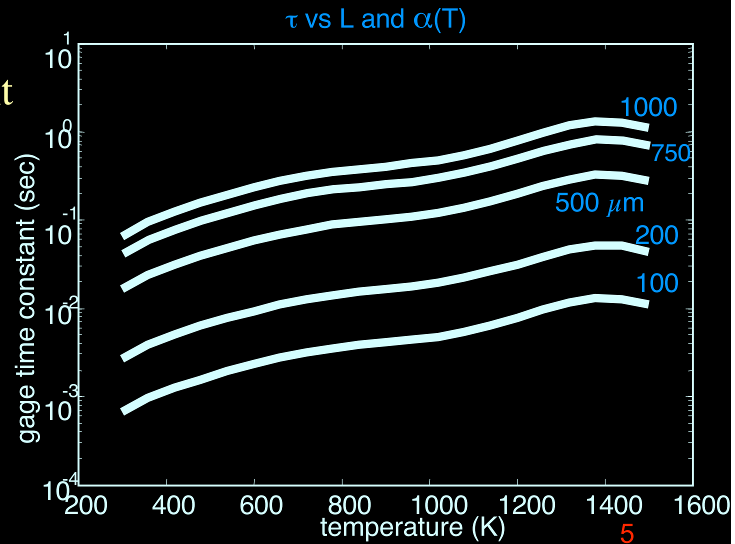
Thermal MicroSensor *System*
Aeroshell and Science

A Monolithic Solid State technology RTD sensor suite has the potential to provide direct measurement of heat flux and temperature measurements



- Absolute upper limits of sensor determined by melting points
  - Platinum 1772 C
  - Alumina 2050 C
- More realistic limit for sensor is 1225 C,
  - which is 28.7 W/cm^2 at radiative equilibrium, and $\varepsilon=1$
  - Ideal for forebody embedded, and afterbody surface.
- Time constant ($\tau=L^2/\alpha$) depends on material thicknesses, properties
  - Vary from 0.05 to 0.2 seconds
  - Fast response necessary to detect transition to turbulence
- Sensor can be tailored for location and type of environment
  - By changing material thicknesses
  - By changing material properties
- Different coatings can be applied to evaluate
  - catalytic heating
  - Radiative versus convective heat flux magnitude

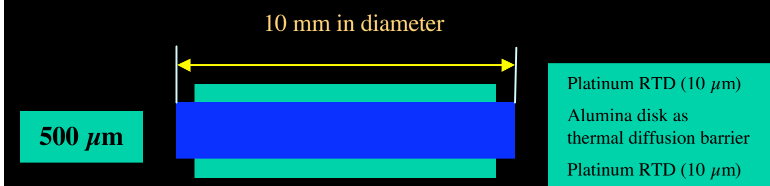


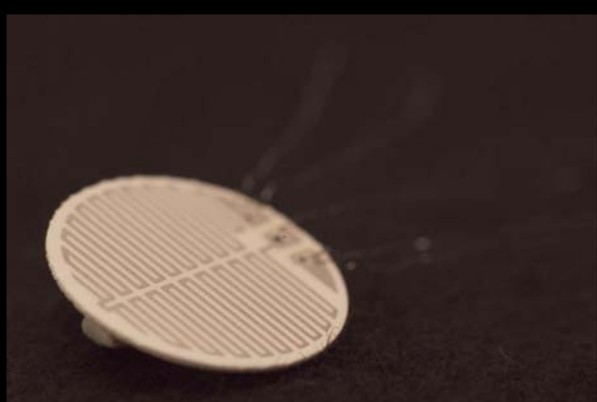


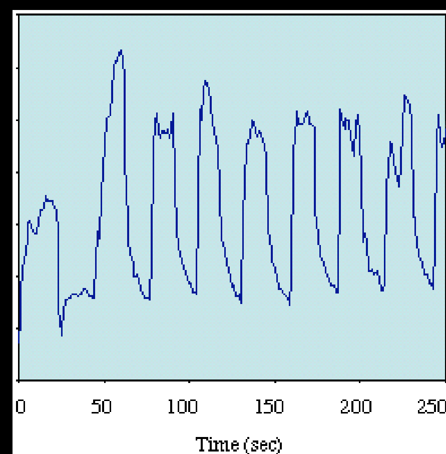
NASA ARC Thermal MicroSensor Overview

Heat Flux & Temperature

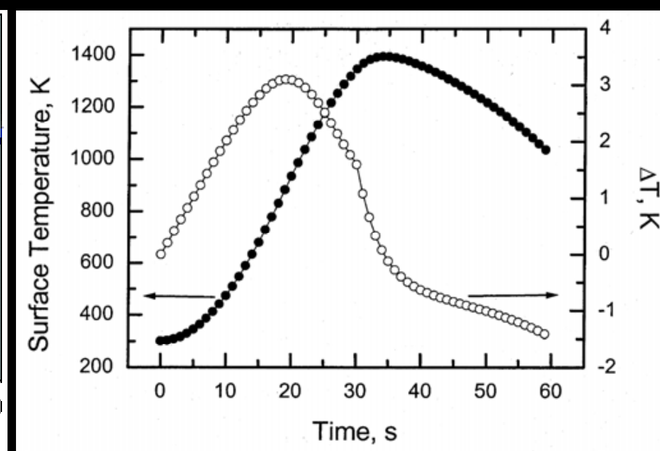
- Currently at Technical Readiness Level 4-5: Monolithic Solid State technology
- Designed and constructed miniature (**1 gram**) heat flux gauges
- Designed and tested electronics with good signal-to-noise ratio for reading the sensor output
- Tested the sensor for response (proof-of-concept) to a chopped air heat input
- Simulated the sensor for response to laser periodic heating







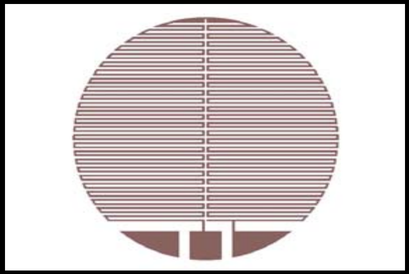
Sensor response to chopped air heating Oishi, UofA, 2001



Simulated sensor response to laser periodic heating. Ref: J.Marschall, SRI, Dec 2001

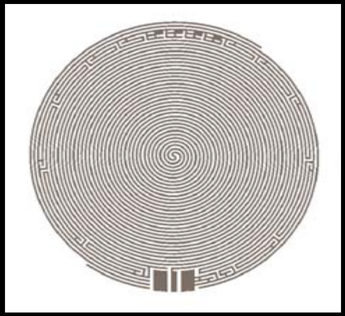
Thermal Sensor Mechanical Evolution
RTD Patterns

Left&Right



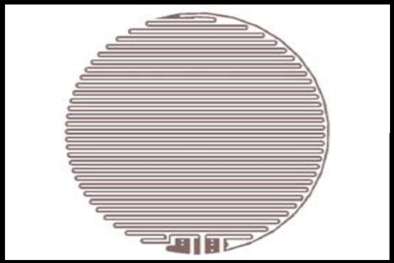
- Pads on one side
- Big gaps around pads for pasting wires by hands

Spiral



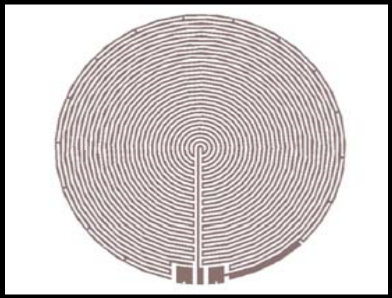
- mid vertical gap removed
- Better resistance adjusting elements
- Print images at unusable area

Up&Down



- Mid vertical gap moved to outward
- Pad size decreased for precision welding

Rings



- Concentric rings to minimize directionality
- mid vertical gap
- Crude resistance adjusting elements

Hexa Spiral

- Pads are distributed along the perimeter

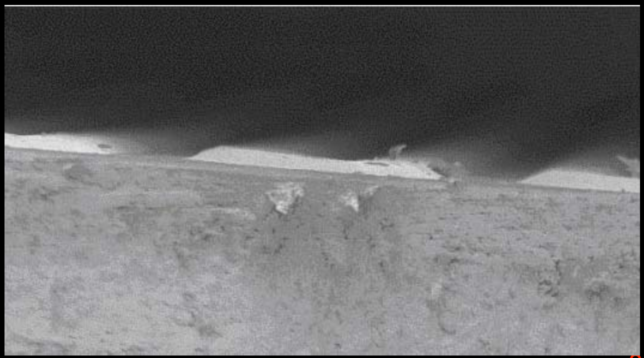
Thermal Sensor
Line Width and Resistance

- Ideally, for a given ink material, RTD resistance is determined by print diameter, line width, and thickness

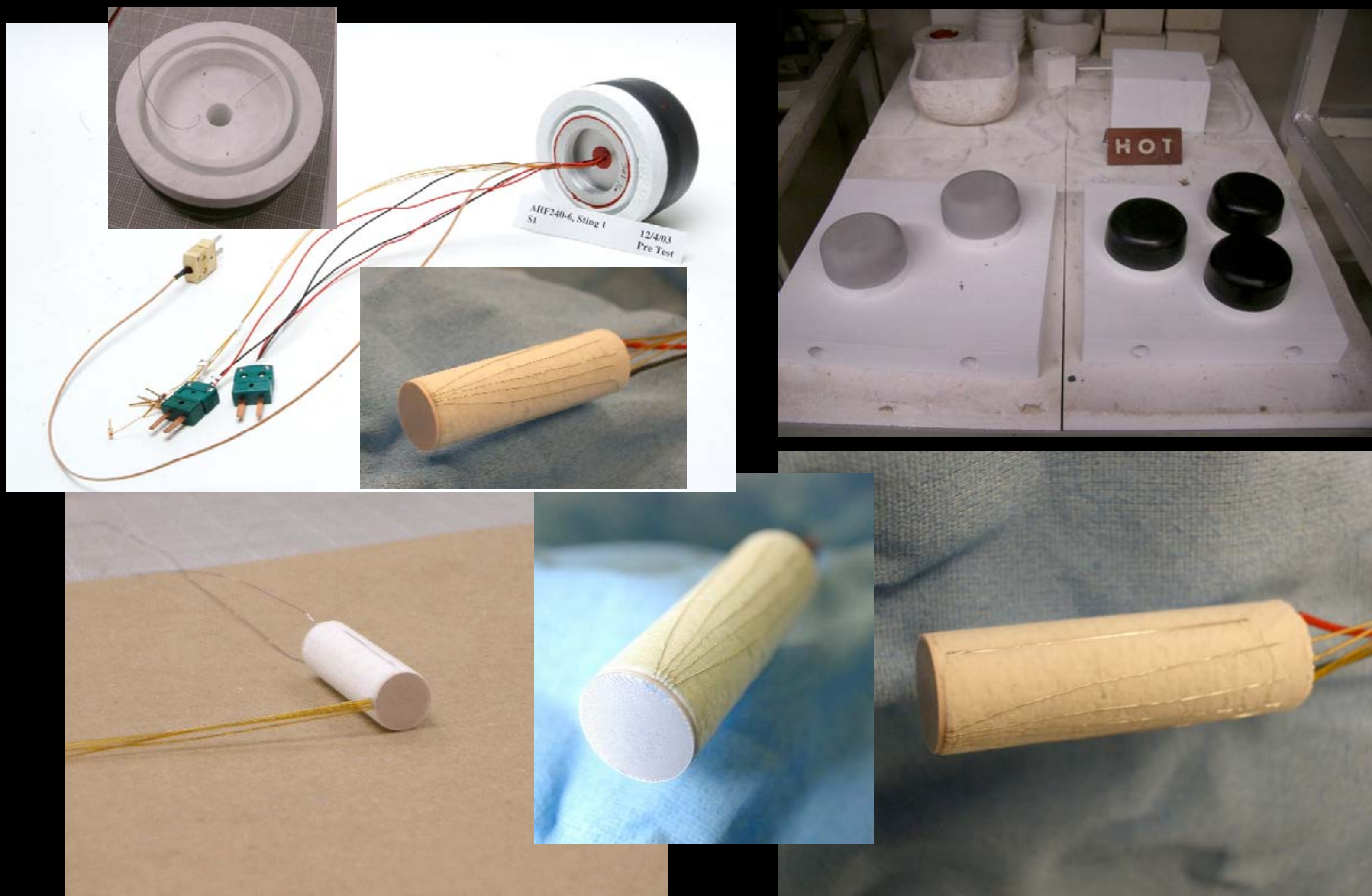
$$Resistance \propto \; diameter^{2} \cdot thickness^{-1} \cdot width^{-2}$$

- Thickness is determined by screen properties: wire size, mesh count, emulsion thickness.
- Width is determined by screen pattern and limited by printability.
- Imperfections in printing: necking and pin holes.

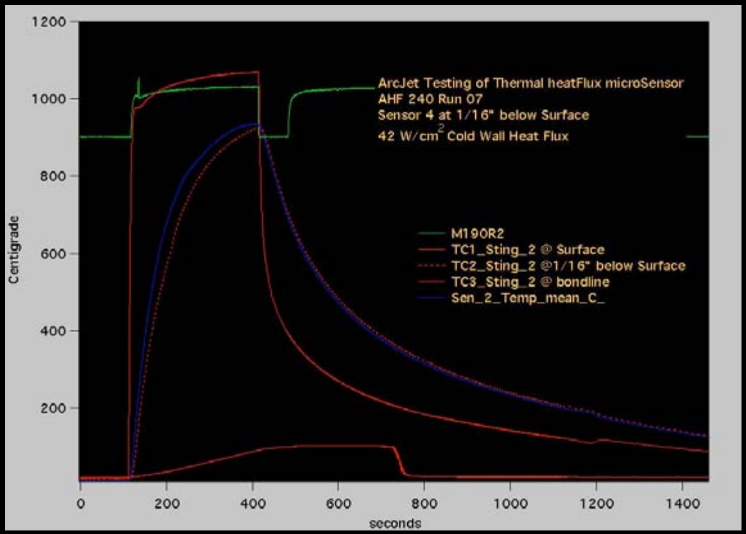
Print Diameter (mm)	Width (micron)	Resistance (Ω)
12.5	100	120
14.5	80	300
14.5	70	440

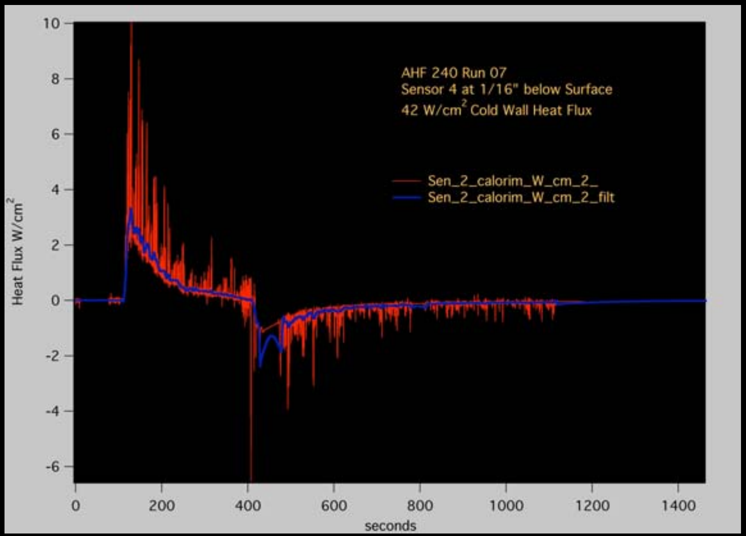


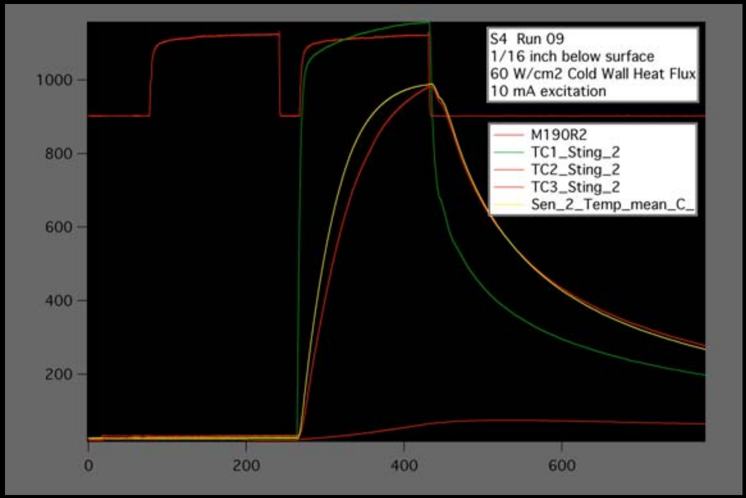
Thermal Sensor
Plug Design and Installation

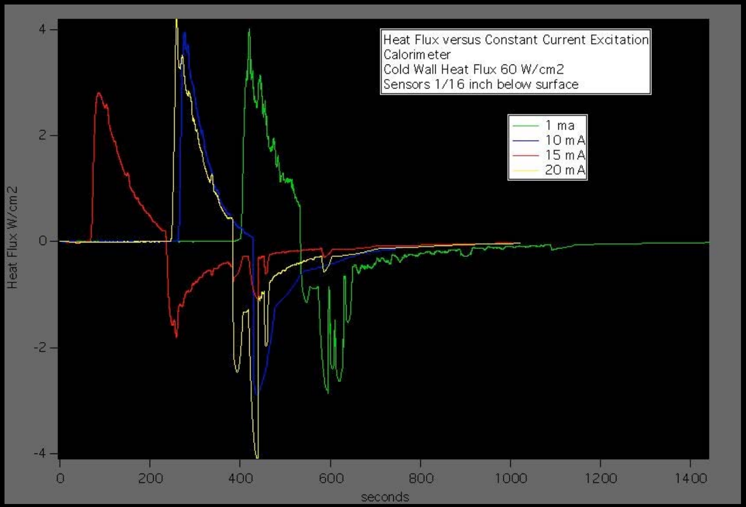


Risk Mitigation ArcJet Testing December 2003



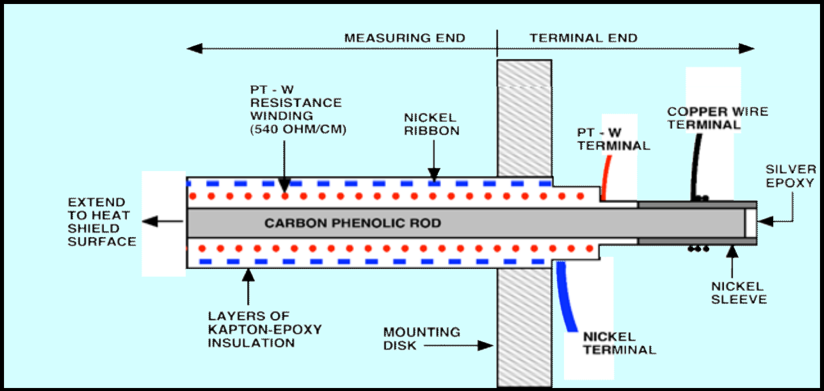


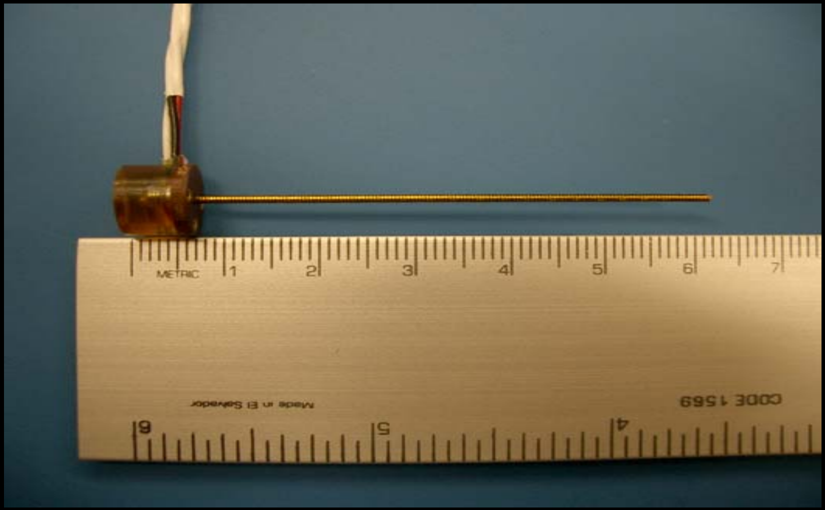




Heat Shield Recession Sensor
ARAD Construction

- Three coaxial conductive elements: Pt-W winding; Nickel ribbon; carbon rod
- Kapton/epoxy provides a tenacious, electrically conductive char
- Ablates at same rate as heat shield with same core material
- Measures a char zone, following a 700 C isotherm **with carbon phenolic core**

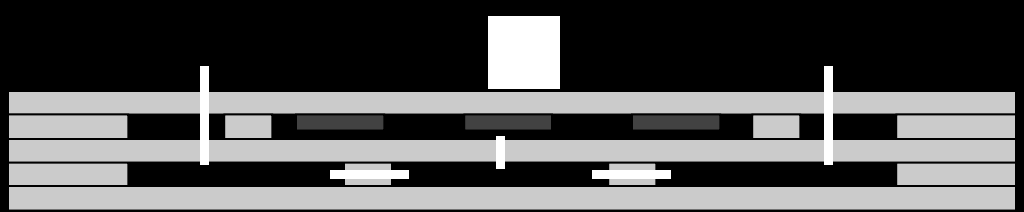


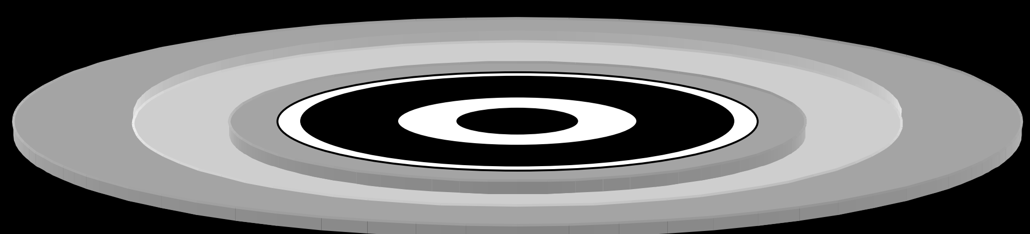


Solid State Pressure Sensor

Initial Design Requirement:

- Measurement Range of 100 atm.
- Measurement duration of 2 hours.
- Operate up to 500 C.
- Mechanical diaphragm strain measurement type.
- Thermal sensor fabrication techniques.
- Same electronics of thermal sensors.





$$v_5 = A_5(v_1 + A_4 v_2) = A_5 i R_{0in} A_1\left[(1 + A_4) f(T) + g(T)(\varepsilon_{in}(p) + A_4 \varepsilon_{out}(p))\right]$$

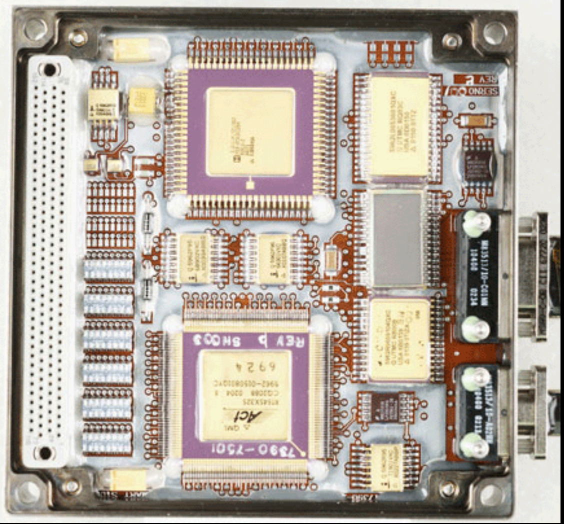
Science Application of Ames MicroSensors

Ames Research Center

- Sensors can be used for measuring temperature and heatflux as part of science measurements
- Suitable for long duration planetary atmospheric and surface and in-depth soil heat transfer measurement for geology (Venus / Mars)
- Atmospheric temperature measurement on probe entry due to fast response, high temperature capability, and high chemical inertness.

Data Acquisition System
ATAS Current Flight Specifications

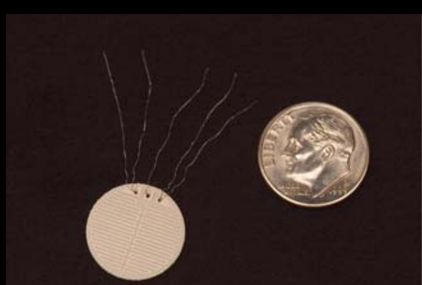
- ***Description:***
- The Aeroshell TRIO Assembly Slice (ATAS) instrumentation is the support electronics for the microSensor and Instrumentation Technology for AeroCapture, or SITAC project. ATAS is capable of reading out 32 sensors, or 64 temperature sensor channels, multiple times per second (10 Hz maximum) for a period of time compatible with Mars atmospheric entry (approximately 165 seconds), and storing the digitized data in internal non-volatile memory. The data is then presented to a spacecraft/host interface at a later time for downlink.

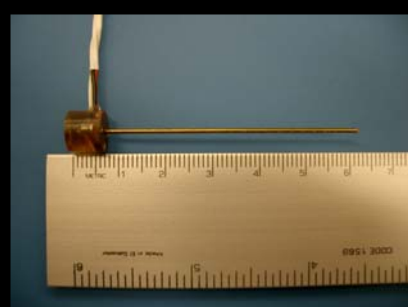


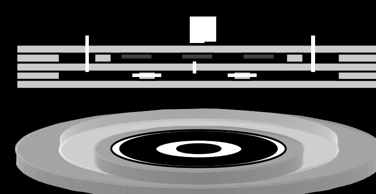
- ***Measurements:***
- 64 Platinum Resistance Temperature Device (RTD) sensors supported
- 2 PRTDs per heat flux sensor
- **10 Samples/second**
- 165 second Sample Period (MSL atmosphere entry time)
- Measurement Resolution:
- **1 °C Absolute**
- Differential:
- **0.01 °C* MSL aft shell heat flux**
- 0.1 °C MSL forebody heat flux
- ***S/C Interface:***
- **Telemetry:**
- Two copies of the following interface are available:
- Data: Outgoing and incoming EIA RS-422 interface for serial data transmission (for electrical purposes only, not signal sense or circuit nomenclature). Data is passed at 38,400 baud using an Instrument Transfer Frame.
- Synchronization: EIA RS-422 electrical interface to receive a nominal 1 pps.
- **Power:**
- 9-pin MDM connector
- Up to 200 mA draw from 5 Volts, +/-10% measured at the instrument connector interface, under maximum load.
- **Mass*:* <700** grams (excluding cables and sensors)**
- **Dimensions*:***
- Aft:10.5cm X 10.5cm X 5cm, 13cm X 5cm footprint
- Forebody**:10.5cm X 10.5cm X 2.5cm, 13cm X 2.5cm footprint

Summary

- NASA has developed the basis for a **plug-and-play sensor system** for aeroshell and science: **Thermal, pressure, and recession**.
- NASA is producing a thermal microsensor **system** and an updated recession sensor (ARAD). They will be integrated with at least two TPS materials for traceability (leading to risk reduction) of TPS and Aeroshell performance suitable for Mars and outer planet missions.
  - Heat flux direct measurement to ~30 W/cm2
  - Temperature to ~1200 C
  - Catalytic vs convective vs radiative heating magnitudes
  - Recession rate and total depth
- Potential application of thermal microsensors for extreme environments science
  - Venus surface and soil high temperatures
  - Jupiter probe temperatures at 100 bar.







Backup

What has been measured in flight?

Ames Research Center

Mission	Instrumentation	TPS Mass Fraction	Observations/Resulting Data	Benefits
Apollo 1-3	• 36 pressure sensors • 35 calorimeters	13.70%	• Reliable data (early in the trajectory) at orbital entry velocities	• Provided data to improve reliability of entry capsule
Apollo 4&6	• 17 pressure sensors • 23 calorimeters • Stagnation and offset radiometers • Heat shield recovered and sectioned		• Reliable data (early in the trajectory) at super-orbital (Trans-Lunar) entry velocities • Reliable radiation data • In-depth characterization of ablating TPS material – lack of recession due to "coking"	• Flight data available basis for quantifying uncertainty in afterbody heating predictions for a lifting entry with an ablating heat shield • Allowed for optimizing heat shield mass and performance
Fire II **Flight for Apollo**	• 3 forebody calorimeters • Stagnation and offset radiometers • 12 afterbody thermocouples • 1 afterbody pressure sensor • Rear-facing radiometer	Flight Experiment Heat shield ejection	• Surface total heating during portion of entry • Total and spectrally resolved incident radiation to surface • Afterbody heating for entire entry • Confirmed lack of neck radiation at superorbital velocities in air	• Provides validation data for aerothermal/air radiation models • Helps quantify uncertainty in afterbody heating predictions
Galileo	• Forebody recession gages • Afterbody thermocouples	**45.4% (FB)** **5% (AB)**	• Largest heat flux and heat load of all planetary missions • Successful demonstration of the ARAD sensor – recession data • Lower than expected recession in the stagnation region • Larger than expected shoulder recession	• Provides the basis for design of the heat shield for Gas Giant entries
Pioneer-Venus (4 probes)	• 2 thermocouples in each heatshield	12.90%	• Massive ablation in the shoulder region (as in the case of Galileo)	• Provides data for design of TPS in the shoulder region
PAET	• Forebody pressure and heat transfer • Thermocouple in TPS near shoulder • Narrow-band radiometers	**13.7% (FB)** **3.5% (AB)**	• Spectrally-resolved radiation over several discrete regions	• Validation data for radiation band models • Data for improvement of heating predictions
RAM-C (1-3)	• Microwave receiver/transmitter • Langmuir probes	Flight Experiment	• Electron number density and temperature in flight • Quantification of radio blackout – cause and effect	• Validation of CFD models
Space Shuttle STS (1-4)	• Pressure and heat transfer sensors (wind and leeside) • Accelerometers and gyroscopes	~16%	• Global and control surface aerodynamics • Demonstration of real-gas effects on vehicle aerodynamics	• Provides data for validation of CFD analysis tools

What has been measured in flight?

Mission	Instrumentation	TPS Mass Fraction	Observations/Resulting Data	Benefits
Viking-I&II	• 2 Backshell thermocouples • Afterbody pressure sensors – limited data	~3.2%	In Progress	• Provided the basis for Mars Pathfinder TPS design • Provided confirmatory data for CFD – afterbody pressure
Mars Path-finder	• 9 in-depth thermocouples in TPS • 3 resistance thermometers	6.2% (FB) 2% (AB)	• 6 functional, including only one on afterbody • 2 functional	• Provided a rationale for MER afterbody heatshield optimization
MER	• None	8.0% (FB) 7.8% (AB)	None	• none

Mars Polar Lander none
Cassini-Huygens: none
Mars Science Laboratory: ?

Table 1 Galileo Probe entry conditions

Condition	Nominal (range)	Actual
Entry velocity, km/s	47.8	47.4
Entry angle, deg	−8.6(±1.4)	−8.4±0.1
Attack angle, deg	0 (0–6)	<7.0
Mole percent He	11 (0–25)	13.6±0.3
Molecular weight	2.22 (2.0–2.5)	2.35[a]
Rotation rate, rpm	10.5±0.5	10.5

[a]Including heavy trace species NH_3 and CH_4 (Ref. 9).

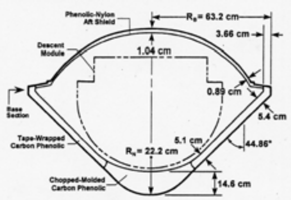


Fig. 1 Cross section of Galileo Probe deceleration module.

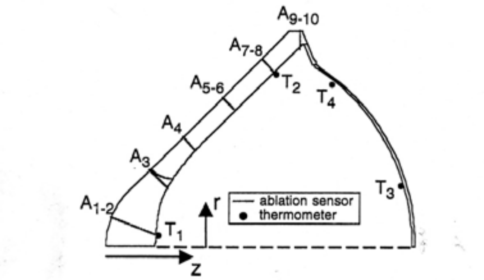


Fig. 2 Locations of 10 ablation sensors (A_1–A_{10}) in heatshield and four resistance thermometers (T_1–T_4) inside structure; sensors are not coplanar.

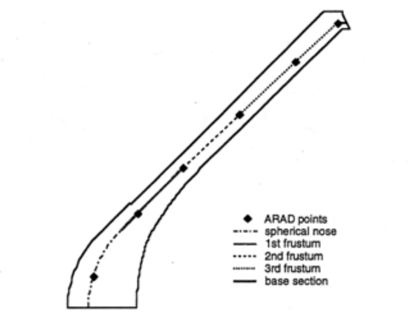


Fig. 5 Reconstruction of heatshield final shape (to scale with initial centerline thickness of 14.6 cm).

Analysis of Galileo Probe
Heatshield Ablation and Temperature Data,
Milos, et. al, Journal of Spacecraft & Rockets 1999

Traceability: Ground Test + CFD

Panel Test Facility

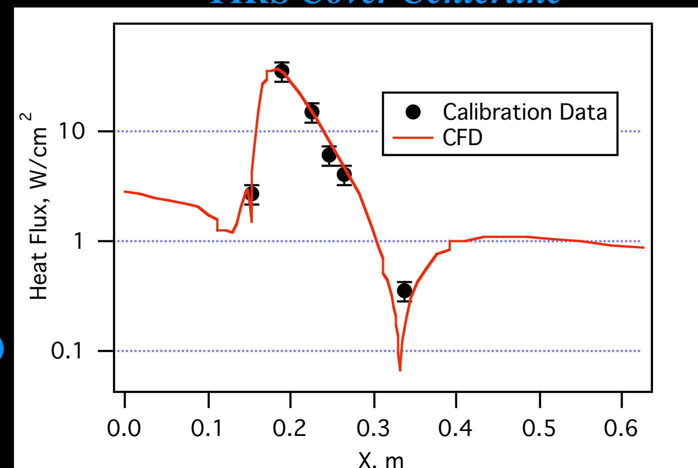
Calibration Test - November 2001

Every opportunity we get, we should fly the right sensor for the right reason - to complete the circle of traceability.

For Mars missions, we know the composition and what we don't is how good is our CFD model and our TPS response model?

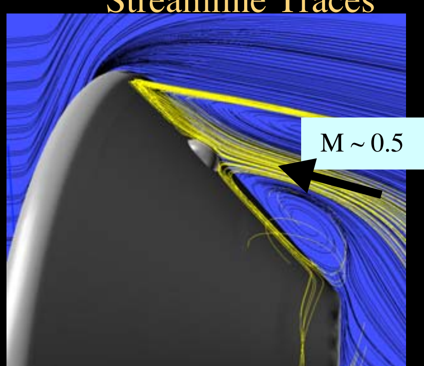
Mars Exploration Rover Aeroshell ArcJet testing & CFD

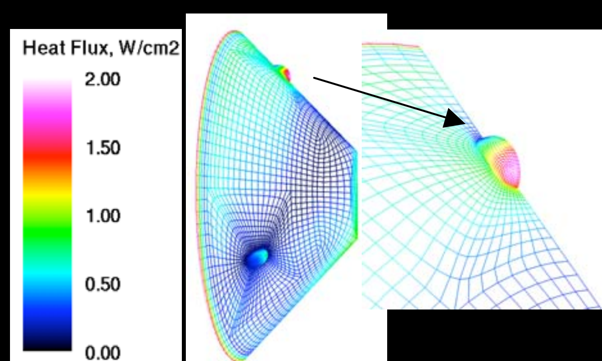
TIRS Cover Centerline



Note: Uncertainty in calibration measurements approximately ± 15%

Streamline Traces





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Arcjet testing

Laminar Heat Flux at Peak Afterbody Heating Condition (t=137.9 s, α= 5 deg)

Risk Mitigation ArcJet Testing
December 2003

Model Name	Sensor location	# of runs	Run index	date	Duration (sec)	Cold Wall Heat flux (W/cm^2)	Sensor current (mA)
S1	1/16	4	1^{st} run06-2	12/04/03	128	41.3	1
			2^{nd} run08-4	12/08/03	183	60.5	1
			3^{rd} run09-1	12/18/03	169	59.6	10
			4^{th} run10-1	12/18/03	167	60.4	15
S2	1.468	1	1^{st} run06-1	12/04/03	30	41.3	1
S3	0.3	2	1^{st} run07-3	12/05/03	302	42.2	1
			2^{nd} run08-1	12/08/03	242	41.0	1
S4	1/16	4	1^{st} run07-1	12/05/03	303	42.2	1
			2^{nd} run08-2	12/08/03	136	41.0	1
			3^{rd} run09-2	12/18/03	168	59.6	10
			4^{th} run10-2	12/18/03	140	60.4	20
S5	0.3	2	1^{st} run07-2	12/05/03	304	42.2	1
			2^{nd} run08-3	12/08/03	243	60.5	1
ARAD	N/A	1	1^{st} run10-3	12/18/03	123	149.7	5